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A CRITICAL LOOK AT
ULTRASONIC WELDING

. . . an evaluation of its capabilities and limitations.

MICHELSON LABORATORIES
U.S. NAVAL ORDNANCE TEST STATION
CHINA LAKE, CALIFORNIA ● OCTOBER 1965

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FOREWORD

Ultrasonic welding, a relatively new process of joining metals, appears to have many desirable features as well as certain limitations. In this article, Thomas Hazlett, a consultant to the U.S. Naval Ordnance Test Station (NOTS), describes exploratory research and experiments that have been conducted in ultrasonic welding and discusses the present state of the art.

In its present stage of process development, ultrasonic welding does not appear to be attractive as a method of joining either thick sheets or high-strength structural alloys. It does, however, appear to be an attractive process for joining soft foils and small electrical leads where heating must be minimized and localized.

Although ultrasonic welding equipment is not available at NOTS at present, the process is of interest at the Station, where new approaches are constantly being sought to expand material processing capabilities and techniques.

This article has been reviewed for technical accuracy by David P. Newman and Alfred S. King.

H. G. WILSON
Associate Technical Director

A CRITICAL LOOK AT ULTRASONIC WELDING

by Thomas H. Hazlett

INTRODUCTION

Kazearski (Ref. 1) states, "No designer of reaction-propelled craft can ignore ultrasonic welding." However, he goes on, "As a process, ultrasonic welding should not be regarded as a cure-all. It will probably never replace any of the existing welding processes." Although neither of these statements is universally accepted by workers in the field, they do highlight the contradictory state of the art at the present time.

The objectives of this paper are (1) to clarify the elements that must be regarded as desirable features of the ultrasonic welding process, (2) to review the current state of the art, and (3) to point out some of the difficulties of the process which may or may not be fully resolved in the future.

First, what is ultrasonic welding? It has been defined as a "non-fusion, solid state, welding process" (Ref. 2). But this definition is open to question by some workers in the field who believe that at least in some cases it is a fusion process on a microscopic scale (Ref. 3). It would, therefore, be better to define ultrasonic welding by showing how it works and by describing the metallurgical reactions that have been proposed.

Ultrasonic welds are achieved by applying a shearing action at the faying surfaces of a lap joint. The shearing movement is very small, but is usually applied in the frequency range of 10 to 20 kilocycles, such motion being produced by transducers which convert high-frequency electrical energy to mechanical motion. Simultaneously, a force is applied normal to the plane of the weld. The term "ultrasonic" refers to the frequency range of the vibrations and does not imply any sonic coupling in the system.

Thomas H. Hazlett, Professor of Mechanical Engineering at the University of California, Berkeley, has been a consultant to the U S Naval Ordnance Test Station for almost 15 years in the field of physical and mechanical metallurgy.

Mr. Hazlett's current research and professional interests include the broad fields of welding, casting, the application of ultrasonics to metal fabrication processes, fracture mechanics, diffusion bonding, high-temperature friction, and the effect of ultra-high thermal flux on materials.

After receiving his B.A. degree in physics and mathematics from Allegheny College, Meadville, Pa., and his M.S. degree in metallurgy from the University of California, Berkeley, he spent 8 years with Lockheed Aircraft Corporation, Burbank, Calif., as a stress analyst and research engineer. He joined the metallurgical group at the University of California in 1948, first as research engineer and later as project engineer in charge of a number of basic sponsored research projects, and became a member of the Engineering Department faculty in 1957.

At present, in addition to his duties as professor at Berkeley and consultant to NOTS, Mr. Hazlett is also an active consultant to industry.

Two systems have been devised for converting the longitudinal motion produced by the transducer into the shearing waves required for welding. These systems are illustrated in Fig. 1. Figure 1a illustrates the angled amplifying horn used to convert longitudinal vibrations to a shear motion, as indicated in the sketch. In this case, a piezoelectric transducer is generally used, and the force normal to the weld plane is achieved manually (not illustrated in the sketch). Figure 1b on the other hand, illustrates a method whereby the longitudinal waves produced by the transducer are converted through a reed coupling system to a shearing action at the weld plane. This system generally utilizes electromagnetic transducers. These will be discussed more fully later. It is also theoretically possible to produce a shearing action directly as illustrated in Fig. 1c. However, as yet this has not been used commercially.

Equipment of the right-angle horn design, as shown in Fig. 1b, is illustrated in Fig. 2a. This device utilizes a piezoelectric ceramic transducer and is satisfactory for welding thin soft materials. Figure 2b shows a commercial machine that is capable of utilizing high clamping forces. Here, the vibrating reed design, similar to that shown in Fig. 1b, is utilized. It may be noted that the clamping force is not imposed directly on the transducer.

In both systems, the amplitude of vibration of the transducer is amplified by a horn that may be of three designs: stepped, conical, or exponential. Each horn has its own characteristics, as described in considerable detail in Ref. 4. A detailed discussion of these horns is not germane to the present report. In general, the conical horn has been used in welding applications. As stated, there are two types of transducers. One makes use of piezoelectric or electrostrictive ceramics, such as barium titanate or lead zirconate titanate, which yield efficiencies of 50 to 60%; and the other utilizes magnetostrictive alloys, such as iron or nickel laminates, which yield much lower efficiencies, of the order of 28 to 30%.

In all ultrasonic welding systems, there is a critical frequency that depends upon the transducer system design and the loading (mechanical impedance). The magnitude of this resonant frequency also varies with the materials being welded. It is therefore important that the transducer be essentially isolated from the clamping force, but recent equipment design has incorporated automatic amplitude tuning that now makes this factor somewhat less critical.
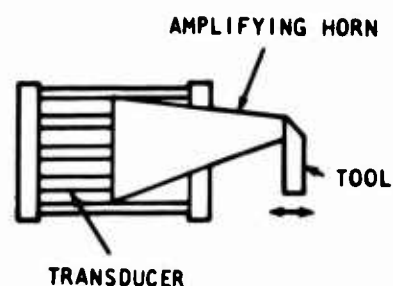
(a) Angle amplifying horn, direct coupling.
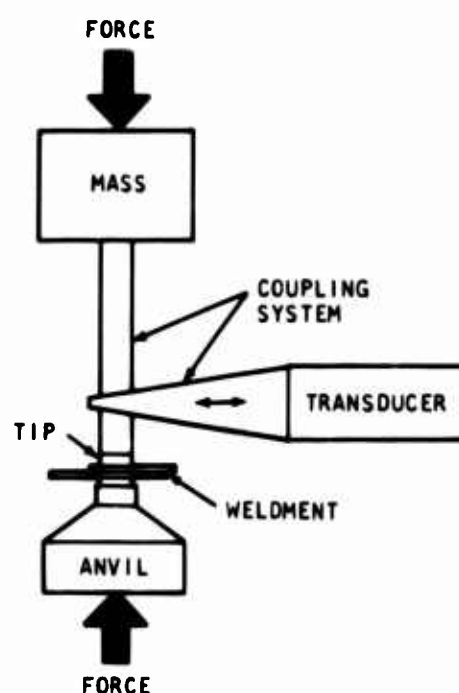
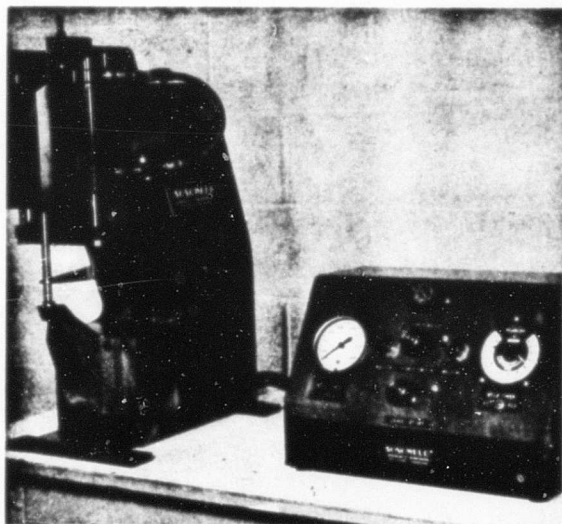

(b) Vibrating reed coupling system.
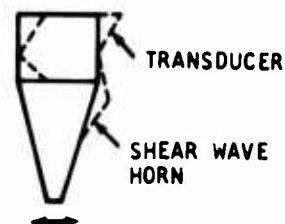
(c) Shear wave horn.

FIG. 1. Schematic Diagram of Various Ultrasonic Welding Systems.

(a) Hand-held model with
piezoelectric transducer.

(b) Vibrating reed system with
electromagnetic transducer.

FIG. 2. Commercial Ultrasonic Welders.

APPLICATIONS OF THE PROCESS

Let us look now to the answers to three important questions regarding ultrasonic welding: (1) what materials can be welded, (2) where can this process be applied, and (3) what are the thickness limitations?

It should be stated categorically that strong, metallurgically sound bonds can be made in most of the common commercial alloys and in a great number of dissimilar metal combinations. Generally, however, the process is more easily applied to thin soft metals.

Ultrasonic welding is being used commercially in several applications to date, the most obvious application being that of joining coils in aluminum foil mills. It has also been designated as a joining process for the "Snap 1A generator" for joining 6061-T6 aluminum to AISI 321 stainless steel (Ref. 1). Also, much work has been done to use the process in the joining of metals that must be used in their unrecrystallized state, such as molybdenum and tungsten. Undoubtedly, other applications unknown to the writer have been made, since the feasibility of joining many other similar and dissimilar metal combinations of various thicknesses has been demonstrated. A number of materials of various thicknesses are shown in Fig. 3 to 7. These photomicrographs illustrate the potential of the process even though it is in its infancy at present.
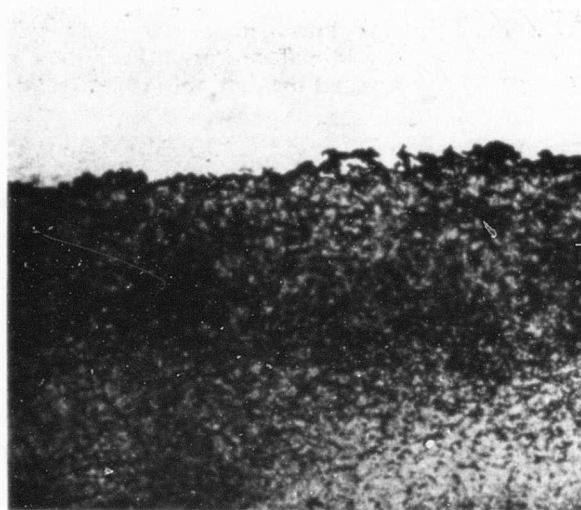

FIG. 3. Ultrasonic Weld Between 0.024-Inch AISI 4130 Stainless Steel and 0.028-Inch A-110AT Titanium Alloy.
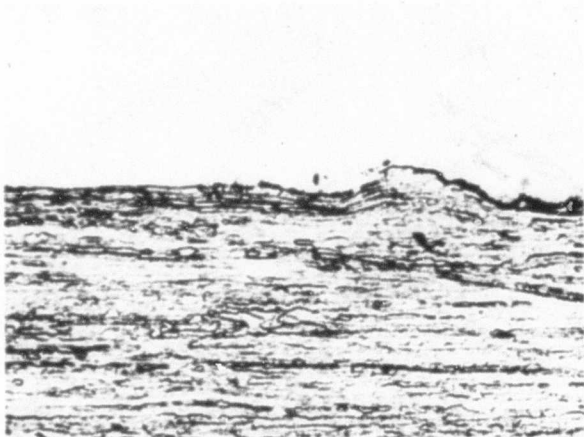
FIG. 4. Ultrasonic Weld Between 0.040-Inch Nickel Wire and 0.020-Inch Molybdenum Sheet.
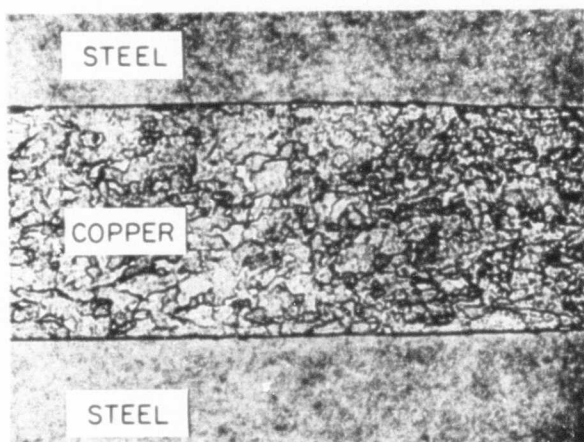

FIG. 5. Ultrasonic Welds Joining Two Sheets of 0.005-Inch AISI 316 Stainless Steel to 0.010-Inch Copper.
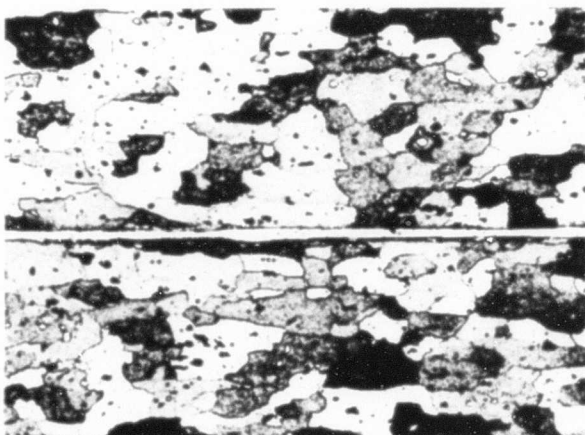

FIG. 6. Two Sheets of 0.040-Inch 2014-T6 Aluminum Alloy Ultrasonically Welded With an 0.001-Inch 1100-0 Aluminum Insert.
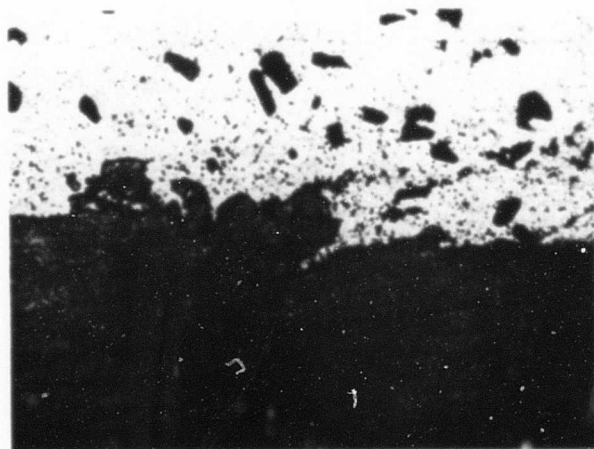

FIG. 7. Ultrasonic Weld Between Aluminum Wire and Copper.

MECHANISMS OF THE PROCESS

Although ultrasonic welding was pioneered about 10 years ago, most of the intervening time has been devoted to equipment design and hit-or-miss empirical attempts to weld various materials. As a consequence, detailed studies of the various parameters involved and of the possible mechanisms of bonding have been delayed until relatively recently.

Jones and DePrisco (Ref. 5) state that the interfacial vibratory energy produced by the ultrasonic welding process ruptures the surface, thereby presenting nascent metal contact. Using thermocouples, they have measured temperatures of from 400 to 600°F in aluminum, which is well below the melting point. They therefore conclude that fusion probably does not occur. The significance of these measurements is questionable. Weare and associates at Battelle Memorial Institute (Ref. 6) suggest that bonding is due to a thin molten film at the interface, but admit of no definite proof. Winter and Neilsen (Ref. 3) propose that ultrasonic welding may occur through the workings of four separate mechanisms:

1. Melting—as possibly evidenced in a lead—tin couple, but the results are not conclusive

2. Mechanical interlock—as evidenced in the copper—silver and copper—nickel couples, in which the interface reaction seems to be one of turbulence and disruption

3. Interfacial atomic forces (nascent bonding)—as evidenced in the

aluminum–aluminum and the
copper–copper bonds in which
the interface quickly disappears

4. Interface chemical reaction—as
evidenced in the copper–zinc
and titanium–molybdenum bonds—
which implies diffusion with a
consequent full range of phases
present in the phase diagram

Evidence for the last mechanism is further supported by the fact that many investigators have observed that high diffusion rates can be induced by ultrasonic vibrations.

Measurements of coupling efficiencies (i.e., the ratio of acoustic power to electric power input) have been made indirectly. These measurements show that the coupling efficiency varies with

1. The material being welded
2. The length of time after the
start of the weld
3. The clamping force

These are summarized in Table 1. The change due to clamping force that occurred with different materials was expected, but the change due to time was unexpected. This may have been caused by the making and breaking of bonding, which resulted in the formation of incipient cracks as a result of "overwelding." The change due to time was not, however, consistent. Much work remains to be done

TABLE 1. COUPLING EFFICIENCY: RATIO OF
ACOUSTIC POWER TO ELECTRIC POWER

Electric power to transducer, 1,600 watts; sheet thickness, 0.028 to 0.032 inch.

Material	Time after start of weld, sec	Efficiency, %	
		250-lb force	750-lb force
1100-H 14 Aluminum	0.2	18.1	26.8
	0.75	18.1	17.2
	1.4	16.2	15.6
2024-T3 Alclad Aluminum	0.2	18.8	16.2
	0.75	13.7	16.2
	1.4	12.5	16.2
CP Copper	0.2	19.4	9.7
	0.75	10.6	8.1
	1.4	10.6	10.3
Armco Iron	0.2	13.0	12.2
	0.75	8.0	13.4
	1.4	10.0	12.2

to gain a better understanding of the fundamental principles involved and of the role played by each of the variables. Although this experimental work will be difficult, it does appear feasible with existing instrumentation and techniques.

FACTORS AFFECTING THE PROCESS

Sufficient work has been done to date to define the major practical factors that affect ultrasonic welding. They are

1. The type and physical condition
of the materials to be welded,
including hardness, surface finish,
and amount of oxide present
2. Welding tip displacement, usually
measured as power into the transducer
3. Welding time
4. Clamping force

For a given material and thickness, there is generally more than one combination of these variables that will produce maximum strength welds. However, as weld time is decreased, power and clamping force must be increased, and the settings become sharply more critical. This is illustrated in Fig. 8. It may be seen from the upper set of curves
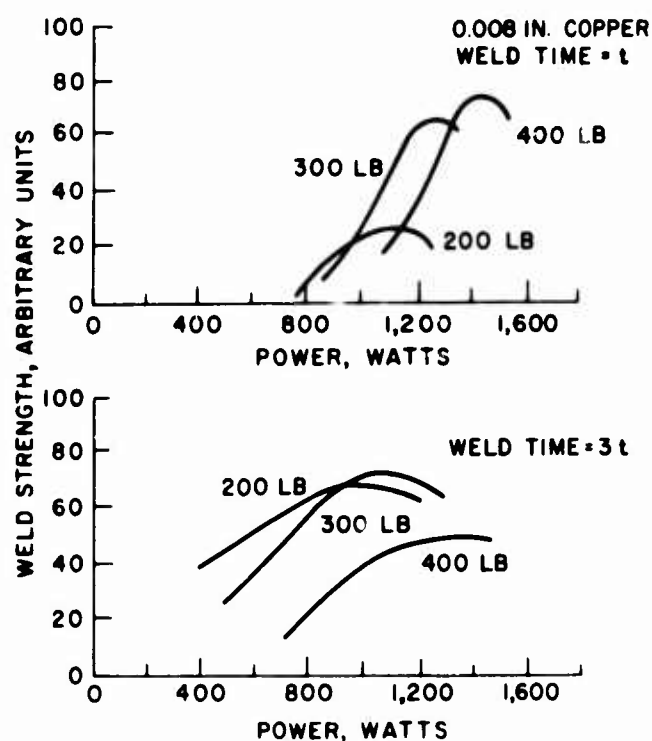

FIG. 8. Effect of Weld Time, Clamping Force, and Power to Transducer on Weld Strength.

that the strength values are critically dependent on the power value for a given clamping force, as compared with longer weld time illustrated on the lower part of the figure. Unfortunately, however, there is evidence to indicate that longer times, particularly at lower power levels, may cause fatigue cracking. This is a subject of considerable controversy at the present time. Various investigators at Battelle claim that cracks are inherent for refractory materials, 17-7PH stainless steel, and aged 2024 aluminum (Ref. 7). Judge, on the other hand, claims that they are not (Ref. 8). Another investigation[1] which utilized 2024-T3 aluminum, B120DCA titanium, 302 stainless steel, and 17-7PH stainless steel, concluded the following:

1. Welds of high strength can be produced without cracks.
2. Cracks adjacent to welds can be produced by "overwelding," i.e., very long times of welding, on materials such as aluminum and 302 stainless steel.
3. Cracks may be produced in all metals by (a) welding too close to the edge, (b) welding conditions that cause adhesion to the tips, and (c) the application of torque stress during welding.
4. After bonding, vibratory energy is widely dispersed, which frequently causes cracking or severe heating at regions remote from the weld.

Comparatively little or no work has been done to distinguish between (1) the strength of the actual bond between two pieces of metal and (2) that contribution to the apparent strength caused by the change of mechanical properties of the materials being welded due to the application of ultrasonic vibration.

However, it appears clear from the work of Langenecker (Ref. 9 and 10) and others that the basic material properties have been altered by being subjected to ultrasonic vibrations. This is also suggested by the work on 17-7PH stainless steel by

[1] Private communication.

workers at Battelle (Ref. 7) and by the author of this report. This is illustrated in Table 2. Although the hardness units are different in the two investigations, the trend may be clearly discerned in both cases. Both investigations showed that annealed material hardens when subjected to ultrasonic vibrations.

However, the data on the heat-treated condition showed differing results: Battelle reported a definite softening in the "T" condition, whereas the other study did not reveal any significant change. The Battelle study showed a definite softening in the "aged" condition, which is probably attributable to overaging. In the second investigation, two results were obtained. The hardness in certain areas

TABLE 2. THE EFFECT OF ULTRASONIC VIBRATIONS ON 17-7PH STAINLESS STEEL

Condition	Untreated	Treated
Battelle Data Two 0.015-Inch Thicknesses; Knoop Hardness Number		
A[a]	185	219
T[b]	346	231
TH-1050[c]	429	244
Author's Data One 0.025-Inch Thickness; Rockwell 30-T Scale		
A[a]	63.5	70
T[b]	83	84.5
TH-1050[c]	89	89 (81)

[a] Annealed
[b] Hardened but not aged
[c] Hardened and aged

of the weld showed that the strength was unaffected by welding conditions, whereas the number in parentheses in Table 2 was obtained in other areas of the weld and shows very definite softening due to overaging. The two different values shown in the second investigation may be attributed to the difference in coupling achieved between the welding tip and the work with nominally the same welding conditions. When good coupling was obtained, the lower value of hardness was secured, whereas with inefficient coupling there was no noticeable change.

LIMITATIONS AND DIFFICULTIES OF THE PROCESS

Although, as pointed out, sound welds may be produced between many materials, both similar and dissimilar, the process is not without serious difficulties and limitations at the present stage of development. The most serious of these appears to be tip sticking and nonuniform coupling. These two effects are interrelated because a high-strength weld depends upon good coupling between the welding tip and the work. In fact, the best coupling depends upon obtaining some contamination of the tip by the materials being welded. On the other hand, when contamination exists, sticking (or bonding) between the tip and the work invariably results. It is claimed by some investigators that this partial tip bonding is the best indication available to the operator that a good weld has been obtained. However, this partial bonding causes poor surface appearance of the weld as well as damage to the tip and anvil. Such damage is shown in the surface appearance of a tip in Fig. 9.

A further difficulty that occurs in current welder systems is that some, if not all, yield transients of high initial power which level out with time. This is shown in Fig 10. Such transients result in relatively uncontrolled initial power, with the result that longer weld times are indicated for a high degree of consistency. However, as indicated, longer weld times are potential causes of fatigue cracking. The designers of welder systems and power supplies may be able to rectify this difficulty, but it does exist in present equipment.

The last problem that appears to be serious is that of nonuniform coupling during welding. Figure 11
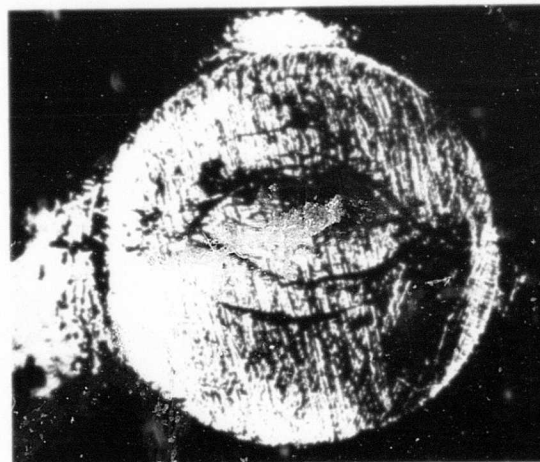

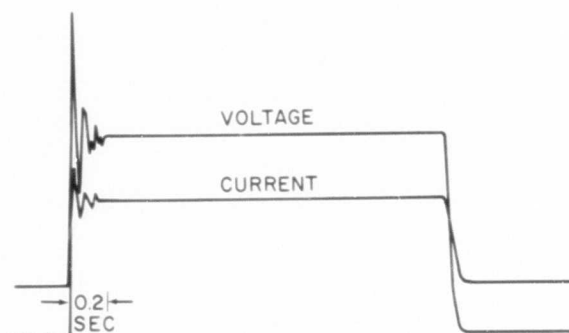FIG. 9. Face of Tool-Steel Tip Showing Fatigue.

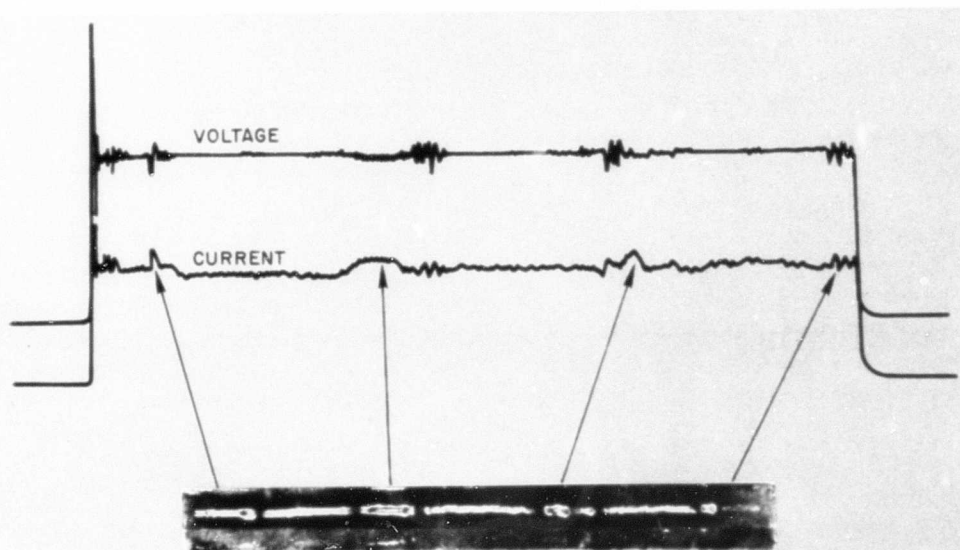FIG. 10. Transient Surges of Power at Initial Phase of Weld Cycle.

FIG. 11. Relationship Between Input Voltage and Current and Coupling of the Ultrasonic Energy to the Work.

9

shows in the bottom portion a simulated roll weld and illustrates the variable results that may occur under nominally constant welding conditions. Light and dark areas are present along the length of the weld, although the input to the equipment was nominally constant. However, monitored recordings of the voltage and current input (upper portion of figure) show that the irregularities in the weld correlate precisely with the irregularities in voltage and current. This may be attributable directly to variation in coupling as the weld progresses, and it represents a very serious problem insofar as weld consistency is concerned.

CONCLUSIONS

From the foregoing, the following conclusions can be drawn as to the state of the art and the current difficulties to be overcome in the process of ultrasonic welding.

1. Metallurgically sound, high-strength bonds can be made between most commercial alloys welded to themselves or to others by this process.

2. The metallurgical mechanisms responsible for ultrasonic bonding are not clear at the present time. Four have been proposed as possibilities; all appear to be effective in bonding.

3. Metal alloys that are impossible to weld by fusion processes because of destruction of desirable properties, such as recrystallization, may be successfully joined by this process.

4. There is a conflict in reliability between short and long weld times; the existence of initial power transients make long weld times desirable, but fatigue cracking is minimized by keeping weld times to a minimum.

5. Efficient coupling is best achieved by some contamination of the welding tip and anvil; however, this appears to be a basic cause of surface roughness of the welded parts and of limited tip and anvil life.

6. Uniform and consistent coupling is difficult or impossible to achieve at the present time, which results in inconsistent weld strengths for critical applications.

7. Although this process has been exploited only a short time, it is expected to find its special place in the joining field; however, much more fundamental, as well as applied, work is required first.

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